H. Long-Life Electrodes for Resistance Spot Welding of Aluminum Sheet Alloys and Coated High-Strength Steel Sheet (USAMP)

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Objectives

- Survey the currently available technology for achieving long electrode life.
- Comparatively test a broad selection of existing and developmental electrode technologies that have technical merit.
- Investigate the electrode wear process through a combination of testing, metallography, and computer modeling.
- Evaluate a "best practice" electrode(s) through beta-site automotive production testing.

Approach

- Conduct benchmarking (Phase 1). The open literature and available corporate literature will be reviewed along with interviews of industry experts in an effort to produce a state-of-the-art report on electrode wear. This phase has been completed.
- Conduct testing (Phase 2). This involves screening of candidate electrode technologies, in-depth testing of electrodes, and beta testing of selected electrode technologies in a production environment.
- Conduct computer modeling (Phase 3) of the electrode metallurgical and mechanical changes that occur as a result of electrode wear. The models will be used to define the mechanism(s) of electrode wear.

Accomplishments

- Finished metallographic investigation of the wear process through a sequential examination of electrode wear for three electrodes using two standard electrode geometries.
- Finished development of computer models to predict electrode life. This includes wear due to both electrode deformation and chemical attack.
- Developed initial description of electrode wear mechanism.
- Continued initial beta site test planning.

Future Direction

- Produce the five electrodes selected for beta site testing.
- Complete planning and execution of beta site tests on hot dip galvanized and galvannealed steels.
- Complete final report on project.

Introduction

Resistance spot welding (RSW) has been heavily adopted by the automotive industry due to its relatively low capital and operating costs and the capacity to support high production rates. RSW is commonly used to weld high-strength steel (HSS) and aluminum in vehicle construction. These materials are commonly selected to reduce vehicle weight and thus improve fuel economy and reduce greenhouse gas emissions. However, electrode wear of coated steels and aluminum continues to be a significant issue. Electrode wear adversely affects the cost and productivity of automotive assembly welding due to reduced weld quality, reliability, and robustness. This mandates increased inspection rates and greater control of welding parameters. Consequently, large potential cost savings and quality improvements are expected from substantial improvements in electrode life.

As technology has developed, few engineering solutions have been successfully introduced into the manufacturing process to manage electrode wear. Weld current steppers and electrode cap dressers have been used for many years, but these techniques do not resolve the underlying causes of electrode degradation. More recent efforts to remedy electrode wear have resulted in innovative electrode technologies, such as new material compositions, material inserts at the electrode face, surface-coated electrodes, and nontraditional electrode geometries (P-, G-, and S-nose). The scope of the present investigation is to objectively evaluate existing and developmental electrode material and geometry technologies to improve electrode life in production.

However, due to technical roadblocks to the development of new electrode materials for aluminum the focus of this year has concentrated on the electrode life of hot dip galvanized (HDG) HSS.

The activities in Phase I, II, and III have been completed this year, and five electrode materials/designs have been identified for limited automotive production trials (beta site tests). The initial planning for these tests is under way.

Previous progress reports have described the results of electrode screening tests on electrode materials/designs that demonstrated improved electrode life under laboratory conditions. This report describes the metallographic results of more detailed sequential life tests, completion of deformation and chemical models describing electrode wear, a description of the mechanisms of electrode wear, and selection of the five electrodes identified for beta site production testing.

Metallographic Evaluation of Sequential Electrode Life Tests on HDG Steel

Sequential evaluation of the stages of electrode wear has been completed for CuZr and two developmental electrode materials (identified as M and R series). An example of the sequential life test results are shown in Figure 1.

Sequential life testing involves the production and metallurgical evaluation of electrodes tested to progressively longer electrode lives. The electrodes were removed after 25, 50, 100, 250, 500, 1000, and 2000 welds and the end-of-life condition. These electrodes were prepared for metallographic examination to show the stages of electrode wear. Optical and scanning electron microscope (SEM) evaluation of the brass phases on the electrode surface were tracked as a function of depth from the electrode face for each electrode. A plot of average brass phase thickness vs number of welds for CuZr E-nose electrodes is shown in Figure 2.

A summary of the brass alloy thickness data is plotted against numbers of welds for each electrode in Figures 3, 4, and 5 for the β brass, γ brass, and total alloy thickness respectively.

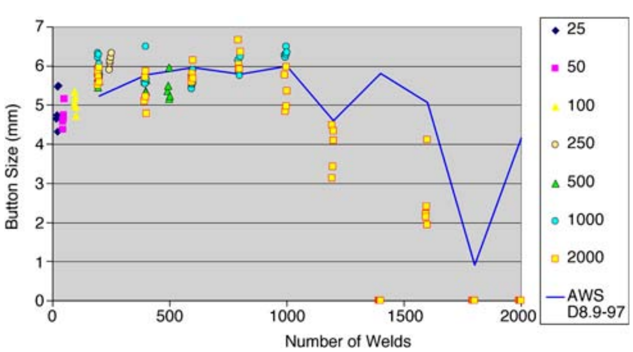

Figure 1. Button size measured during interrupted electrode life tests with CuZr electrodes on 1.1-mm, 350-MPa HDG steel (solid line indicates AWS D8.9 results).

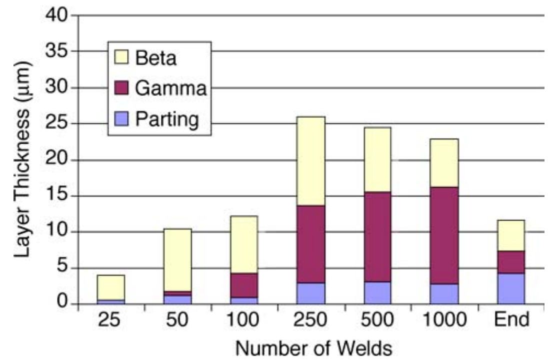

Figure 2. Total alloy thickness present on the electrode face after sequential life testing CuZr E-nose-style electrodes (Series A) on 1.1-mm HDG HSS. (Electrode life tests were interrupted, and the electrodes were extracted for metallographic examination after predefined numbers. Brass phase identification was made using EDAX. Brass phase thickness was made using SEM.)

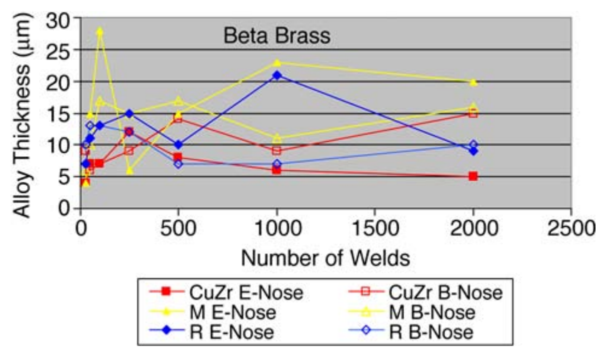

Figure 3. Summary of β brass alloy layer thickness plotted as a function of numbers of welds for CuZr, M, and R materials. (Filled symbols are E-nose-style, and open symbols are B-nose-style electrodes.)

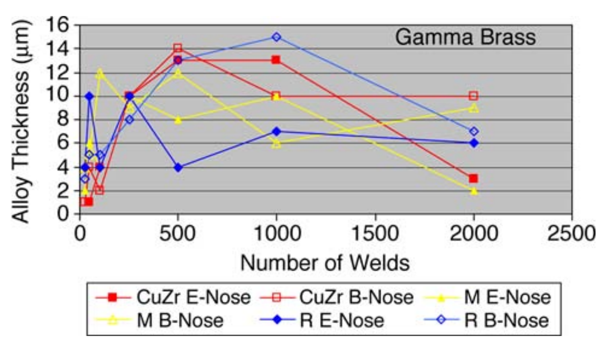

Figure 4. Summary of γ brass alloy layer thickness plotted as a function of numbers of welds for CuZr, M, and R materials. (Filled symbols are E-nose-style, and open symbols are B-nose-style electrodes.)

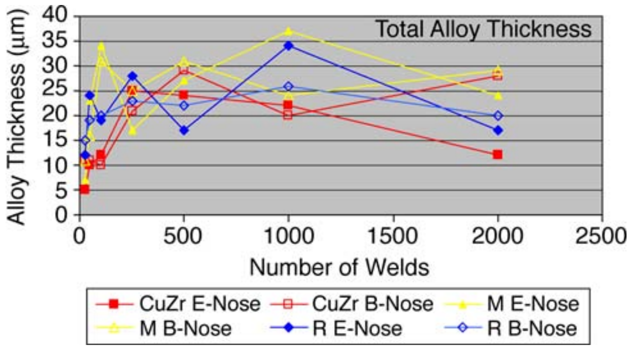

Figure 5. Summary of total alloy thickness plotted as a function of numbers of welds for CuZr, M, and R materials. (Filled symbols are E-nose-style, and open symbols are B-nose-style electrodes.)

The β brass on the electrode face forms first, followed by the γ brass. Between 250 and 500 welds, all of the electrodes had reached equilibrium. The average maximum thickness of the β brass occurred at about 100 welds, while the average maximum thickness of γ brass occurred at about 250 welds.

The ratio of β brass to γ brass thickness after 1000 welds ranked well with both overall electrode life and the onset of button size instability measured during the AWS D8.9 tests. This is the result of thermal conditions on the electrode face. It appears that γ brass is favored for electrodes that operate at higher interface temperatures or exposed to more severe service conditions. Beta brass is softer than gamma brass, and the data suggest that softer brass phases on the electrode face may decrease resistive heating and extend electrode life.

This analysis is further amplified by plotting microhardness contours across ½ of the electrode face for the CuZr and M electrodes. Examples of the hardness matrices after 500 welds of wear are shown in Figures 6 and 7. Figure 6 shows that softening is largely limited to 500 µm below the electrode face for the CuZr electrode, with extreme softening at the face. Heavy softening occurred along an elliptical contour with the greatest softening at the centerline and the least softening at the electrode edge. The hardness along the outside surface of the electrode body remains hard, except near the electrode face.

Hardness contour for the M electrode after 500 welds in Figure 7 shows that the overall hardness is

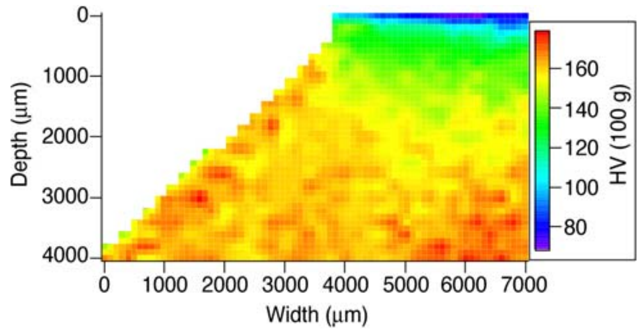

Figure 6. Contour plot of microhardness measurements systematically made over half of the sequential life test CuZr E-nose-style electrode extracted after 500 welds. (Color scale represents hardness as a function of depth from the electrode face and distance from the centerline.)

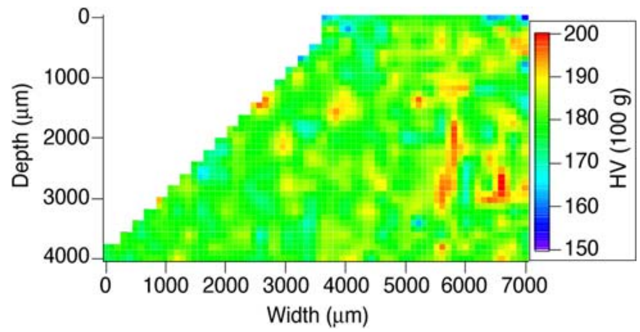

Figure 7. Contour plot of microhardness measurements systematically made over half of the sequential life test M material E-nose-style electrode extracted after 500 welds. (Color scale represents hardness as a function of depth from the electrode face and distance form the centerline.)

much greater than the CuZr electrode at room temperature. This electrode is characterized by hard and soft randomly spaced regions. The electrode face does not exhibit any significant softening as observed on the CuZr electrode. The centerline of the electrode appears to have strengthened during electrode life with some very hard regions directly below the electrode face.

Optical metallographic examination of the M electrodes showed a few instances of deep cracks oriented along the body and emanating from the electrode face. These cracks appeared after 500 and 1000 welds of wear. Zinc was shown to flow into the cracked regions. Another observation characterizing the M electrodes was the apparent intermixing of β and γ brass layers at specific points on the electrode face.

The R material showed typical alloy layers characteristic of CuZr electrodes. However, this material showed excessive pitting. In several instances, metal flow into pits was observed. Compared to M material, the β and γ brass alloy layers for the R electrodes were well delineated.

Models of Deformation and Chemical Attack of Electrodes on HDG Steel

Electrode face enlargement was modeled as both electrode deformation (extrusion) and surface chemical erosion. These two modes were identified to provide significant contributions to electrode wear.

Electrode deformation contributes to electrode face enlargement through incremental flow of electrode material from the face during welding. Analytical expressions of stress-strain characteristic as a function of temperature, degradation of material properties with numbers of spot welds, and variation in peak temperature at the electrode surface were coupled to predict the growth of electrode face diameter as a function of numbers of welds. Using the deformation models, predictions of electrode face diameter can be made for various electrode material properties and welding conditions. The applied stress from the electrodes and the weld time are integrated into the model. The strain in the copper electrode at the electrode-sheet interface during one spot weld was estimated. The strain from subsequent welds accumulates with a specific efficiency. The amount of strain was related to the stress-strain characteristic and its measured tempering behavior. The model assumes that the deformation is limited to a small disk of material at the electrode face. The size of the disk increases with progressive electrode wear. Deformation of the disk ceases when the applied stress at temperature falls below the yield stress at temperature. Although it ignores many of the numerous intricacies of the mechanical deformation process, the predicted change in face diameter is in good agreement with typical test data and practical experience. The model was a useful tool for predicting "what if" scenarios during analysis of the sequential life data.

The chemical effects were calculated from diffusion-controlled growth models assuming the copper is in contact with an infinite supply of zinc. Appropriate temperature dependencies were applied to the one-dimensional diffusion model. Two cases were considered: face operating temperatures below and above the melting point of zinc. For the first case, solid state diffusion was found to be much too slow to describe the rate of brass alloy formation shown in Figure 2. For the second case, the zinc diffuses rapidly into the zinc/copper interface, which rapidly penetrates into the copper. The resulting brass layers formed close to the rate of brass formation depth found in this program as shown in Figure 2. An example of brass formation at 450°C is given in Figure 8.

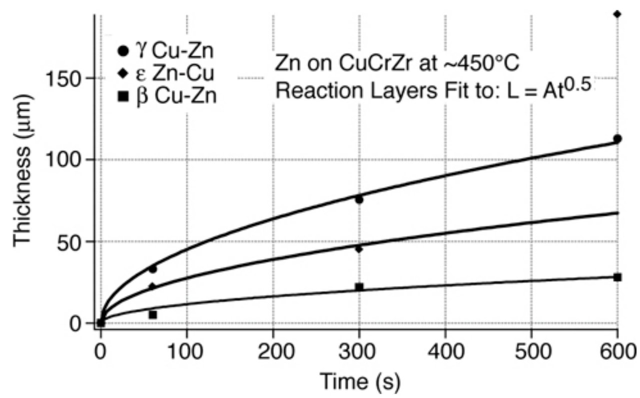

Figure 8. Plot of β, γ, and ε brass thickness as a function of time at 450°C.

Mechanisms of Electrode Wear

The electrode wear process in RSW of galvanized HSS was shown in this program to be limited by

1. current density, and
2. weld nugget instability.

These two factors combine to produce the rapid degradation of button size often observed at the end of electrode life.

The typical weld setup produces a large weld with fresh caps. First, electrode face diameter enlargement decreases the current density and decreases the size of the weld. Large welds are relatively insensitive to the factors that contribute to weld nugget establishment. However, as the weld size decreases toward minimum button size, weld size is controlled more by nugget establishment factors and less by maximum nugget growth factors (retention of the molten weld nugget without weld metal expulsion). This makes the weld very sensitive to bulk and interface resistance heating and to the increase in heat extraction due to electrode face enlargement. (This was tracked to a decrease in nugget penetration for one electrode, suggesting that extraction of heat from the sheet surfaces limited nugget penetration and made weld establishment less stable as predicted from one deformation model.) Because nearly all of the typical welding process factors contribute to nugget establishment and early growth, the nugget becomes instable and thus exhibits the tendency for precipitous drops in weld button size.

Two approaches were envisioned to improve electrode life. These were based on

1. maintaining a low electrode-sheet interface temperature, and
2. sacrificial electrode nose.

Both approaches were found to improve electrode life in these tests. These two approaches operate on very different principles, and the beta site tests will largely focus on the first approach.

The second approach was found to offer the best performance of any of the electrodes tested. The benefits of this approach were shown to occur through the development of a "protrusion" on the face of the electrode. This protrusion enhances and maintains current density during electrode wear. It occurs for electrodes with very high electrode-sheet interface operating temperature. The exact mechanism responsible for maintaining the protrusion is not fully understood at present.

Electrodes for Beta Site Tests

Stepper-current type electrode life will be evaluated in the beta site tests. The conclusions from this work and taking into account the type of galvanized sheet and application-specific characteristics were combined to recommend five electrodes for beta site production testing:

- G-cap or P-cap electrodes produced from M or oxide-dispersion-strengthened electrode material,
- E-cap electrodes produced from M electrode material with reduced face thickness,
- B-cap electrodes produced from M electrode material with reduced face thickness,
- E-cap electrodes produced from CuZr material with reduced face thickness and internal fins, and
- B-cap electrodes produced from CuZr material with reduced face thickness and internal fins.

All of the electrodes will be produced as female caps in a 16-mm body with a 6-mm face diameter. These electrodes follow the principles governing the two approaches for improving electrode life listed earlier.

Conclusions

The completion of Phases I, II, and III of this program have yielded several electrode materials and electrode designs that will be tested in automotive production environments. These electrodes were selected based on a hypothesis of electrode wear in HDG steels. This hypothesis is based on a progressive loss in current density and development of weld nugget instability due to the governing welding conditions and enhanced heat extraction from enlarged electrode face diameter.

Extension of electrode life of aluminum is possible, but fell outside the scope of this program. Electrode life on aluminum is fundamentally different from welding coated steels. The development of effective electrodes for aluminum will require more study involving more than modified electrode material and geometry.

Future Work

The electrode life models developed in this program should be further refined. The extrusion and chemical dissolution models should be coupled into a single model that incorporates welding parameters. These changes should greatly enhance the combined models predictive capability and make it much more useful for predicting such things as optimized weld schedules.

Optimization of the electrode composition and design was not possible in this study. However, the critical electrode material characteristics have been identified. Further copper alloy development on targeted copper systems should prove invaluable in producing an "ideal" electrode material. Additionally, optimization of the electrode design would include engineering heat flow to the water-cooling channel and define the rate of electrode face enlargement.

The mechanics of copper extrusion and brass alloy formation should be studied more systematically to better describe the events contributing to electrode face enlargement and nugget stability. The electrodes and the steel sheets should be instrumented, and these dynamic measurements used as inputs to computer models to validate the end-of-life test conditions.

These tests should extend to steels outside of the steel gauge, coating type, and power supply type used in this program. The welds should be metallographically examined to further understand the nugget stability conditions at the end of electrode life.

The development of protrusions on the electrode face should be studied further to optimize the sacrificial behavior and perhaps incorporate this into standard electrode cap designs. This would be done by better understanding the nature of extrusion and the equilibrium conditions that interact to produce the protrusion. Because the weld face runs very hot in this style of electrode, the effect of face temperature on nugget formation should be further evaluated.

Presentations and Publications

1. M. Gallagher, K. S. B. Athwal, and R. Bowers, “Electrode Wear Characterization in Resistance Spot Welding,” *Proc. of Sheet Metal Welding Conference XI, Sterling Heights, Michigan, May 11–14, 2004*.
2. W. Peterson, J. Gould, R. Bowers, M. L. Santella, and S. S. Babu, “Evaluation of Electrode Design and Materials for Improved Electrode Life,” *Proc. of Sheet Metal Welding Conference XI, Sterling Heights, Michigan, May 11–14, 2004*.
3. S. S. Babu, M. L. Santella, and W. Peterson, “Modeling Resistance Spot Welding Electrode Life,” *Proc. of Sheet Metal Welding Conference XI, Sterling Heights, Michigan, May 11–14, 2004*.
4. S. S. Babu, M. L. Santella, W. Peterson, J. E. Gould, “Modeling resistance spot welding electrode life,” AWS Welding Show, April 2004, Chicago, Illinois.